

## AN ULTRA-WIDE BAND SOIL/TIRE INTERACTION RADAR

FIELD OF THE INVENTION

1  
2 [1] The present invention relates to the application of wideband  
3 radar signals. In particular, the present invention is directed  
4 toward a technique for using wideband radar signals to measure the  
5 interaction between a tire and the soil in vehicle mobility  
6 assessment.

BACKGROUND OF THE INVENTION

7  
8 [2] Wheeled vehicle mobility depends in part on the interface  
9 between the tire and the on- or off-road surfaces on which the  
10 tire is operating. Studies of the interaction between a tire and  
11 soil, as a vehicle moves off-road, provides engineers information  
12 from which to draw conclusions about optimum tire design to  
13 maximize performance of the vehicle.

14  
15 [3] Traction of a wheeled vehicle is dependent largely upon the  
16 footprint of the tire. As soil deforms below the tire, the tire  
17 will passively shape itself to this deformation. Immobilization  
18 of the vehicle occurs when the sinkage of the tire and the net  
19 pull of all tires on the vehicle (referred to as "drawbar pull")  
20 reduce the traction of the vehicle to zero.

21

22 [4] The interaction of vehicle tires and the soil is a subject of  
23 great concern. In military and emergency vehicle applications,  
24 vehicle immobilization can have disastrous results. Moreover, an  
25 increasing number of civilian vehicles (e.g., SUVs, light trucks,  
26 and the like) are marketed with both off- and on-road  
27 capabilities. Thus, there is a pressing need to be able to study  
28 the interaction of vehicle tires and soil.

29

30 [5] However, tire/soil interaction is difficult to study in real  
31 time since the presence of the tire itself prevents direct  
32 observations of any rutting or slippage under dynamic loading  
33 conditions. Large discontinuous deformations of soils are a key  
34 problem in vehicle mobility developments. Any attempt to place  
35 sensors in the soil may result in an intrusion into the soil  
36 resulting in variation in the soil parameters which the tire sees.  
37 Thus, what is required in the art is a method and apparatus which  
38 aids in the real-time study of soil/tire interaction.

39

40 [6] In addition to testing purposes, a means of gathering  
41 tire/surface data in real time may be useful for other purposes as  
42 well. For example, such a system could be used with on-board  
43 vehicle traction control, dynamic braking (e.g., anti-lock  
44 controls), vehicle yaw controls, tire inflation and monitoring

45 systems, and the like.

46  
47 [7] Such real-time data could be used to monitor relative  
48 traction at a given wheel and thus control power application to a  
49 given wheel before slippage occurs (as opposed to many present  
50 systems, which require wheel slippage before a given wheel is de-  
51 powered). Moreover, such real-time data could be useful in  
52 advising a driver of on- or off-road surface conditions (e.g.,  
53 icing, snow, mud viscosity, and the like). Thus, for example, a  
54 driver could be alerted to the presence of black ice.

55  
56 [8] Prior art tire testing systems generally deal with looking  
57 for defects (occlusions and the like) within tires for production  
58 testing purposes, or are directed toward on-road testing  
59 techniques. Jones et al., U.S. Patent No. 5,837,897, issued  
60 November 17, 1998 and incorporated herein by reference, discloses  
61 an ultrasonic device for tire testing which may be used to  
62 determine tire pressure.

63  
64 [9] Matrascia, et al., U.S. Patent No. 5, 777,220, issued July 7,  
65 1998 and incorporated herein by reference, discloses a testing  
66 braking and traction of a wheel. Matrascia places the wheel/tire  
67 assembly onto a roller representing a road surface and tests the  
68 tire in that environment. Such testing techniques are known in

69 the art, and while may provide adequate tire/road data, do not  
70 provide *in situ* tire/road data or off-road tire/soil data. Boyd,  
71 U.S. Patent No. 3, 948,080, issued April 6, 1976, and incorporated  
72 herein by reference, discloses an apparatus for testing traction  
73 properties of pneumatic tires. Boyd provides a wheel with an  
74 instrumented hub which is then placed on a test trailer which is  
75 towed over a road surface. While this system may provide *in situ*  
76 data, it may have limited use in off-road data acquisition.  
77 Moreover, the apparatus does not provide real-time data on tire  
78 footprint or soil depression.

79  
80 [10] Recent advances in micro-impulse radar technology (MIR) have  
81 been developed at Lawrence Livermore Laboratories. Thomas E.  
82 McEwan has developed a number of applications for MIR technology.  
83 Representative of this technology is McEwan, U.S. Patent No.  
84 5,757,320, issued May 26, 1998 and incorporated herein by  
85 reference. MIR technology has been applied to a number of areas,  
86 including hidden object locators (i.e., "stud finder"), ground  
87 radar for finding buried objects (e.g., pipes, cables, and the  
88 like) as well as proximity sensors for car parking and cruise  
89 control systems. Some of these technologies are presently in  
90 production and may be commercially available.

91  
92 [11] However, to date, applicant is not aware of any activity,

other than the inventor's, in applying MIR or other types of radar technology to the field of tire testing, particularly for off-road tire testing to quantify tire/soil interaction.

#### SUMMARY OF THE INVENTION

[12] The present invention comprises a radar system which may be mounted within the casing of a vehicle tire to measure the location of the inner casing of the tire (tire deformation) as well as the location of the tire/soil interface (tire footprint).

The radar system of the present invention may also be used to determine soil characteristics by analyzing the reflected signals.

[13] The present invention may have particular use in testing tires for use with on- or off-road surfaces. However, the present invention may also be used to monitor tire deformation, traction, footprint, and soil characteristics.

[14] The present invention comprises a system for generating at least one of tire, ground, and tire/ground data for a pneumatic tire having a casing forming a hollow inner portion for containing a gas, the pneumatic tire being in contact with a ground surface.

The system comprises a radar transmitter, located within the hollow inner portion of the pneumatic tire, for generating a radar

117 signal towards a portion of the pneumatic tire in contact with the  
118 ground surface. A radar receiver receives a reflected signal from  
119 at least one of an interface between the gas and the casing and an  
120 interface between the casing and the ground surface. A means is  
121 provided for analyzing the reflected signal to produce at least  
122 one of tire, ground, and tire/ground data.

123

124 [15] In the system of the present invention, the radar signal may  
125 comprise an ultra-wide band radar pulse. The radar transmitter  
126 comprises a pulse repetition rate function generator for  
127 generating a pulse signal for triggering a radar pulse, an impulse  
128 function generator, coupled to the pulse repetition rate function  
129 generator, for receiving the pulse signal and generating a wide-  
130 band radar impulse in response to the pulse signal, a first  
131 amplifier, coupled to the impulse function generator, for  
132 amplifying the radar impulse and outputting an amplified radar  
133 impulse, a waveguide, coupled to the amplifier, for receiving and  
134 transmitting the amplified radar impulse, and a feedhorn, coupled  
135 to the waveguide, for receiving the amplified radar impulse and  
136 transmitting the radar impulse toward the tire casing.

137

138 [16] The radar comprises a switch, coupled to the pulse repetition  
139 rate generator and the radar feedhorn, for alternately receiving  
140 an input pulse from the pulse repetition rate generator and radar

141 return signals from the radar feedhorn, a second amplifier,  
142 coupled to the switch, for amplifying the input pulse and the  
143 radar return signals, a detector, coupled to the second amplifier,  
144 for detecting radar return pulse data from the radar return  
145 signals, and a data port, coupled to the detector, for outputting  
146 radar return pulse data.

147  
148 [17] The apparatus of the present invention may map dynamic  
149 deflection of the tire. To this end, the invention provides  
150 insight into contours of the tire during interaction of the tire  
151 and any contact surface. Definition of contact surfaces as a  
152 result of theses internal tire contours provides information  
153 supporting objective quantification of traction performance of a  
154 tire. The device provides insight into claims of tire  
155 manufacturers regarding the ability of the tire to prevent  
156 hydroplaning of wet surface. Furthermore, the device, when used  
157 in conjunction with central tire inflation systems and active  
158 suspension systems, may provide required information such that the  
159 devices can react to limitations in traction. Moreover, given  
160 that ride performance and tire traction of a vehicle are directly  
161 related to pressure, contact pressure, and dynamic deflections of  
162 the tire, the device may be used to support research, testing, and  
163 development in this arena.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[18] Figure 1 is a side view schematic illustrating how an ultra-wideband radar may be attached internally to a wheel of a test vehicle in one embodiment of the present invention.

[19] Figure 2 is a more detailed illustration of how reflections of radar waves 160 of Figure 1 occur in air/tire interface 180 and tire/soil interface 190.

[20] Figure 3 is a block diagram of the ultra-wide band impulse radar of a first embodiment of the present invention.

[21] Figure 4 is a block diagram of an alternative embodiment of the present invention incorporating a transceiver with dual feed horn antennas.

[22] Figure 5 is a waveform diagram illustrating the pulsed waveform generated by the impulse function block.

[23] Figure 6 is a waveform diagram illustrating the reflected signal with interface returns.



**DETAILED DESCRIPTION OF THE INVENTION**

[24] Figure 1 is a side view schematic illustrating how an ultra-wideband radar 130 may be attached internally to a tire 110 of a test vehicle in one embodiment of the present invention. A slip ring (not shown) may be attached to the circumference of tire 110 and is used to maintain radar 130 in a vertical direction, pointing at the off road surface 170.

[25] Waveguide 120 may encircle the slip ring and vehicle axle 150 to provide adequate travel time for the signal. Radar waves 160 from waveguide 120 may be fed to feed horn 140 which directs such waves downward through the tread of tire 110 to soil 170. Reflected waves 160 from soil 170 are fed back through feed horn 140 and waveguide 120 to electronics 130.

[26] Data may be collected by focusing the ultra-wideband radar signals at the ground during testing. Radar 130 picks up signals indicative of the deformation of the soil below tire 110. These data are calibrated against external data and used to estimate stress and strain imposed on soil media 170.

212 [27] Figure 2 is a more detailed illustration of how reflections  
213 of radar waves 160 of Figure 1 occur in air/tire interface 180 and  
214 tire/soil interface 190. Radar waves 160 of Figure 1 are  
215 illustrated in Figure 2 as source radar waves 164 and reflected  
216 radar waves 162 and 166.

217  
218 [28] Radar reflections are generally generated at the boundaries  
219 or surfaces between two materials having different impedances.  
220 Thus, a first reflection 166 may occur at the air/tire interface  
221 180 between the air within tire 110 and the inner surface of tire  
222 110. A second reflection 162 may occur at the tire/soil interface  
223 190 between the outer surface of tire 110 and soil 170. First  
224 reflection 166 may be useful in determining the amount of tire  
225 deformation. Second reflection 162 may be useful in determining  
226 tire footprint, or how much soil 170 has deformed in response to  
227 the presence of tire 110.

228  
229 [29] Reflected signals 162 and 166 may be analyzed in radar  
230 electronics 130 or using an external waveform analyzer or computer  
231 software applying known signal processing techniques to determine  
232 where the reflections occurred and what was the nature of the  
233 media. Location of reflection 166, for example, will indicate how  
234 much the casing of tire 110 has deflected due to the load of the  
235 vehicle and the type of soil 170. Location of reflection 162 may

236 indicate how large the tire footprint is (e.g., how much tire is  
237 in contact with soil 170).

238

239 [30] Reflections from more than one location within the casing of  
240 tire 110 may be used to determine this overall footprint size.  
241 Alternately, sampled points may be measured and data extrapolated  
242 to determine tire footprint size. Finally, the nature of the  
243 reflected signal may be used to determine soil type and  
244 characteristics (e.g., rock, mud, clay, sand, or the like).

245

246 [31] Figure 3 is a block diagram of the ultra-wide band impulse  
247 radar of a first embodiment of the present invention. Elements  
248 310, 320, 330, and 390 form the transmitter portion of the first  
249 embodiment of the present invention. In Figure 3, PRR (Pulse  
250 Repetition Rate) function 310 generates a pulse signal at a  
251 predetermined rate. The time period of the pulse rate should be  
252 greater than the amount of time for the radar signal to be  
253 transmitted to the air/tire and tire/soil interfaces, and return,  
254 to prevent interference between adjacent pulse signals.

255

256 [32] Impulse function generator 320 shapes each pulse from the  
257 pulse rate signal into a wide-band radar impulse as illustrated in  
258 Figure 5. The radar impulse of Figure 5 may comprise a high  
259 voltage near-instantaneous pulse having a pulse width  $t$  on the

order of 100 picoseconds in length. The output of impulse function generator 320 may then be fed to amplifier 330 which amplifies the radar signal and outputs the impulse function signal through waveguide 390 through feedhorn antenna 340.

[33] Elements 350, 360, 370, and 380 comprise the receiver of the first embodiment of the present invention. Switch 380 may alternately receive the input pulse repetition rate signal from PRR function 310 or radar return signals from feed horn antenna 340. These signals may be amplified in amplifier 370 and fed to detector 360 and communications port ("comm port") 350. Analysis of the resultant data signals may thus occur in an external data analysis device receiving data through com port 350. Alternately data may be analyzed within the device through the use of suitable electronics.

[34] Figure 4 is a block diagram of an alternative embodiment of the present invention incorporating a transceiver with dual feed horn antennas. In the apparatus of Figure 4, elements 410, 420, 430, 490, and 440 comprise the transmitter portion of the alternative embodiment of the present invention. In Figure 4, PRR (Pulse Repetition Radar) function 410 generates a pulse repetition rate signal. Impulse function generator 420 shapes this signal into an ultra-wide band radar impulse as illustrated in Figure 5.

284 The radar impulse of Figure 5 may comprise a high voltage near-  
285 instantaneous pulse on the order of 100 picoseconds in length.  
286 The output of impulse function generator 420 may then be fed to  
287 amplifier 430 which amplifies the ultra-wide band radar signal and  
288 outputs the signal through waveguide 490 through feedhorn antenna  
289 440.

290  
291 [35] Elements 450, 460, 470, 480, 495, and 445 comprise the  
292 receiver of the first embodiment of the present invention. In the  
293 embodiment of Figure 4, a separate receiving feed horn antenna 445  
294 may receive reflected radar signals from the air/tire interface or  
295 the tire/soil interface. These received signals may be fed to  
296 switch 280 through waveguide 495.

297  
298 [36] Switch 480 may alternately receive the input pulse repetition  
299 rate signal from PRR function 410 or radar return signals from  
300 receive feed horn antenna 445. These signals may be amplified in  
301 amplifier 470 and fed to detector 460 and com port 450. Analysis  
302 of the resultant data signals may thus occur in an external data  
303 analysis device receiving data through com port 450. Alternately  
304 data may be analyzed within the device through the use of suitable  
305 electronics.

306  
307 [37] Figure 6 is a waveform diagram illustrating the reflected

308 signal with interface returns. With known media parameters, the  
309 reflected signals at the air/tire and tire/soil interfaces may be  
310 analyzed for time of flight and media characteristics. As  
311 illustrated in Figure 6, the large initial pulse A represents the  
312 initial radar impulse generated by the radar. The next, more  
313 attenuated, pulse B represents the reflection from the air/tire  
314 interface.

315  
316 [38] The time distance between the two pulses represents the  
317 distance between the tire inner casing and the radar feedhorn.  
318 Thus, tire deflection can be measured accurately by measuring the  
319 time differences between these two pulses. In addition, other  
320 parameters of the second pulse, such as amplitude and duration,  
321 may provide information as to the amount of tire casing deflected.

322  
323 [39] The next, and even more attenuated, pulse C illustrated in  
324 Figure 6 is generated by the tire/soil interface. Again, the  
325 distance between these pulses may represent a distance between the  
326 tire/soil interface and the feed horn. Again, the amplitude and  
327 duration of the pulse may be indicative of other features, such as  
328 tire footprint, soil type, and the like. In addition, a number of  
329 feedhorns may be directed at different portions within the tire  
330 casing to generate multiple radar data sets to map tire casing and  
331 tire/soil interface behavior.

332

333 [40] While the preferred embodiment and various alternative  
334 embodiments of the invention have been disclosed and described in  
335 detail herein, it may be apparent to those skilled in the art that  
336 various changes in form and detail may be made therein without  
337 departing from the spirit and scope thereof.

338

339 [41] For example, while the present invention has been disclosed  
340 in the context of tire and vehicle testing, the availability of  
341 such real-time data could be used in modern day vehicle control  
342 systems to provide additional data inputs on parameters such as  
343 tire inflation, wheel slippage, and other traction data.  
344 Moreover, with the increased availability of low-cost micro-  
345 impulse radars, such systems could be implemented at fairly  
346 reasonable costs.

347

348 [42] For example, in a traction control embodiment, such real-time  
349 data could be used to monitor relative traction at a given wheel  
350 and thus control power application to a given wheel before  
351 slippage occurs. In contrast, most Prior Art systems require  
352 wheel slippage before a given wheel is de-powered. Similarly,  
353 such a system could be used to monitor wheel slippage for braking  
354 purposes as a sensor input to an anti-lock braking system to  
355 provide an indication of wheel locking before wheel lock actually

356 occurs. Again, the in Prior Art, many such systems required  
357 actual wheel lock to occur before releasing braking pressure to a  
358 given wheel.

359

360 [43] In a tire inflation monitoring embodiment, signals from the  
361 air/tire interface could be used to indicate effective tire  
362 diameter and thus tire inflation level. Low tire pressures could  
363 be alerted to the driver or used to activate on-board tire  
364 inflation systems.

365

366 [44] In addition, such real-time data could be useful in advising  
367 a driver of on- or off-road surface conditions (e.g., icing, snow,  
368 mud viscosity, and the like). Thus, for example, a driver could  
369 be alerted to the presence of black ice, which may appear to the  
370 eye as water. Similarly, a driver could be apprised as to soil  
371 conditions (e.g., mud viscosity) without having to exit the  
372 vehicle. A driver could be warned, for example, if the system  
373 detects deep mush which could cause the vehicle to be immobilized.  
374 The driver could then retreat and try a different course without  
375 being stuck in deep mud.